

Primordial Proto–Galaxies

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ABSTRACT

The first stars to form in protogalaxies must have primordial chemical composition. We refer to a protogalaxy that is forming stars of primordial composition, or very low metallicity ($Z \leq 0.01Z_{\odot}$), as “Primordial Proto–Galaxy” (PPG). PPGs contain little or no dust, and therefore their spectral energy distribution can be modelled from the rest–frame ultraviolet to the infrared without accounting for dust extinction and emission. We present the results of computing the photometric properties of high redshift PPGs at near–to–mid infrared wavelengths, that will soon be available with the new generation of infrared space telescopes, such as SIRTf and the NGST. We show that: i) PPGs at very high redshift ($5 < z < 10$) should be easily selected from deep near/mid IR surveys with a colour–colour criterion; ii) PPGs at redshift $5 < z < 10$ can be detected at $8 \mu\text{m}$ with the NGST, if they have a constant star formation rate of at least $100 M_{\odot}/\text{yr}$; iii) once the redshift of a PPG photometric candidate is determined, its near–to–mid infrared colors should provide strong constraints on the stellar IMF at zero or very low metallicity.

1 INTRODUCTION

Photometric redshifts have been used very successfully in the last few years to select high redshift galaxies ($z > 2$) detected with deep surveys such as the HDF (e.g. Driver et al. (1998) and ref. therein). Star forming galaxies have been discovered out to redshift $z = 6.7$ (Chen, Lanzetta & Pascarelle 1999). At $z > 5$, traditional optical bands (U, B, V, R) fall below the rest frame wavelength that corresponds to the Lyman break spectral feature (1200 \AA), where most of the stellar radiation is extinguished either by interstellar or intergalactic hydrogen. Because of this, galaxies at $z > 5$ are practically invisible at those photometric bands, and even if they were detected, their colors would provide very little information about their stellar population. New detectors and space telescopes, such as SIRTf, and in particular the NGST, will offer the possibility of detecting very distant galaxies at IR wavelengths, and of using photometric redshifts also with far–IR colors, as proposed by Simpson & Eisenhardt (1999).

Nearby star forming galaxies are known to contain a considerable amount of dust, that extinguishes a large fraction of their stellar UV light and boosts, even by orders of magnitude, their IR luminosity. The effect of dust must be taken into account in the computation of colors involving photometric bands that span a large wavelength interval. However, the search for very young proto–galaxies, perhaps the first star forming systems in the Universe, might be pursued without having to model the effects of dust. The first stars to form in proto–galaxies must have primordial chemical composition, or at least very low metallicity (e.g. Padoan, Jimenez & Jones 1997). Although it is difficult to model the formation and disruption of dust grains on a galactic scale, it is likely that the dust content of a galaxy grows together with its metallicity, and that a proto–galaxy with primordial chemical composition or very low metallicity ($Z \leq 0.01Z_{\odot}$) has practically no dust (Jimenez et al.

1999). In this work we refer to young protogalaxies with metallicity $Z \leq 0.01Z_{\odot}$ as primordial protogalaxies, or PPGs.

In the next section we compute the IR color evolution with redshift of PPGs with $Z = 0.01Z_{\odot}$, and show that PPGs at redshift $5 < z < 10$ have IR colors similar to those of nearby ($z < 0.5$) young stellar populations with metallicity slightly under the solar value and with no dust. However, nearby galaxies are either forming stars and contain dust (spiral, irregular and starburst galaxies), or have lost most gas and dust and are not forming stars anymore (elliptical galaxies), and in both cases they are even redder than high redshift PPGs. In §3 we show that, because of their very blue colour, PPGs do not suffer from very strong cosmological dimming, a feature which should aid their detectability in deep infrared surveys with the NGST. If nearby galaxies ($z < 0.5$), with infrared colors similar to PPGs, did exist (though very rare), they could be distinguished from PPGs because they would be spatially resolved.

Star forming gas of primordial composition is likely to be warmer than present-day molecular gas, because it is cooled mainly by molecular hydrogen, to temperatures probably in excess of 100 K. This relatively warm temperature is likely to affect the stellar initial mass function (IMF). In §4 we show that, once the redshift of a PPG photometric candidate is determined, near-to-mid IR colors can provide constraints on the stellar IMF. For example, a stellar IMF containing as many stars with mass $M < 5M_{\odot}$ as the solar neighborhood IMF could potentially be readily excluded by the mid-IR colors, in favor of an IMF with no stars with mass $M < 5M_{\odot}$. In §5 we briefly discuss the performance of the broad band selection of PPGs, versus emission line searches, and show that the broad band photometry is probably convenient. Our conclusions are summarized in §6.

2 SPECTRAL ENERGY DISTRIBUTION AND IR COLORS OF PPGs

One of the most difficult problems in the study of star forming galaxies at high redshift is to quantify the effect of dust upon their spectral energy distribution (SED). The largely unknown effect of dust results into a very uncertain conversion from UV and (sub-)mm luminosities to star formation rates (e.g. Pettini et al. (1998); Jimenez et al. (1999); Peacock et al. (1999)). Uncertainties in the temperature, geometry, and amount of dust in high redshift galaxies are the main sources of errors in the estimate of star formation rates in the high redshift Universe (Jimenez et al. 1999).

Traditional near infrared band colors (e.g. $J - K$) of galaxies at redshift $2 < z < 4$ are not strongly affected by dust extinction (at most 0.5 mag in reasonable models – Jimenez et al. (1999)). In contrast, colors of high-redshift objects derived from combining photometric bands spanning a larger range of wavelengths can be much more severely affected by the presence of dust, both due to dust extinction in the rest-frame UV, and dust emission in the rest-frame IR and near-IR. However, very young proto-galaxies of primordial chemical compositions, or at least very low metallicity ($Z \leq 0.01Z_{\odot}$), are likely to have little or no dust. Because of the absence of dust and of the extremely low metallicity (and perhaps of their “massive” stellar IMF – see §4), PPGs are the rest-frame bluest stellar systems in the Universe. In fact, in the redshift interval $5 < z < 10$, they have colours similar to the colours of nearby ($z < 0.5$) idealized starbursts with no dust and slightly sub-solar metallicity. They are definitely bluer than nearby real starbursts and elliptical galaxies, and even bluer than nearby star forming disc and irregular galaxies (see Figure 2).

We have computed the SED of PPGs using the extensive set of synthetic stellar population models developed in Jimenez et al. (1998); Jimenez et al. (1999). In particular, PPGs are modelled using a constant star formation rate and $Z = 0.01Z_{\odot}$ metallicity. As noted above, we expect (and therefore assume) that no photo-metrically significant quantity of dust has already been formed in PPGs. We also assume that PPGs are young objects (age less or equal than 100 million years). Furthermore, and in order to test our primordial IMF hypothesis – see §4, we have adopted a Salpeter IMF ($x = -1.35$) with four different low mass cutoff values: 0.1, 2, 5 and $10 M_{\odot}$ (i.e. the IMF does not contain any stars with masses below the cut-off values).

The effect of the different low mass cutoff values on the SED of a PPG is shown in Figure 1, where the flux density F_{ν} is plotted in arbitrary units for a 10 million year old PPG with $Z = 0.01Z_{\odot}$ and constant star formation (solid lines). Different solid lines corresponds to the different IMF cutoffs, 0.1, 2, 5 and $10 M_{\odot}$, from top to bottom (the 5 and $10 M_{\odot}$ are almost overlapped). As expected, the lack of low mass stars translates into a deficit of flux at IR wavelengths. Furthermore, for a low mass cutoff larger than $5 M_{\odot}$ the SEDs do not differ much since stars with masses larger than $5 M_{\odot}$ have similar spectral energy distributions in the IR. The difference in relative flux density over the wide wavelength range illustrated in Figure 1 provides the means to test the IMF in PPGs – see §4. The SED of an observed nearby starburst, from Schmitt et al. (1997), is also plotted in Figure 1 (dashed line), together with a 10 million year model starburst, with continuous star formation, metallicity $Z = 0.2Z_{\odot}$, and no dust extinction or emission (dotted line). The difference in the spectral slope between PPGs and nearby starbursts is striking, and it is still significant between PPGs and the idealized starburst model with no dust. Although the idealized starburst model with no dust is unlikely to describe any galaxy

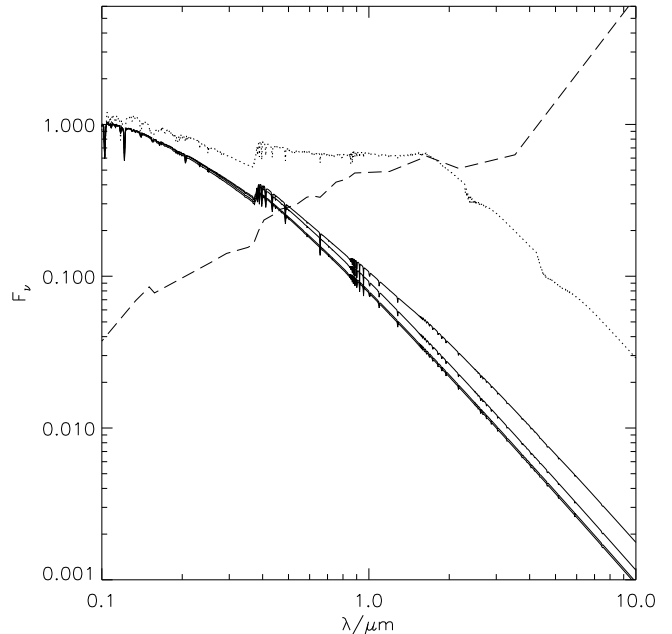


Figure 1. Spectral energy distribution for a starburst with constant star formation rate, age of 10 million years, metallicity $Z = 0.01Z_{\odot}$ and a Salpeter ($x = -1.35$) IMF with four different lower mass cutoffs: 0.1, 2.0, 5.0 and $10.0 M_{\odot}$ (solid lines), from top to bottom. Starbursts with no low mass stars ($< 5 M_{\odot}$) are about a factor of 2 fainter than starbursts with low mass stars ($> 0.1 M_{\odot}$), at $3 \mu\text{m}$. Note that for cutoff masses larger than $5 M_{\odot}$, the spectral energy distribution changes very little, making our predictions almost independent of the exact value of the cutoff mass. The models have been normalised at 1000 \AA . Also shown is a solar metallicity starburst from Schmitt et al. (1997) (dashed line). We finally plot an idealized starburst model with constant star formation rate, Salpeter IMF, age of 10 million years, $Z = 0.2Z_{\odot}$ and no dust (dotted line). The UV SED of this starburst can be a rough approximation of the UV SED of quasars.

observed nearby, it can be used as an approximate model for the UV SED of quasars, due to its rather flat SED in the far ultra violet wavelengths.

We have computed AB magnitudes ($m_{AB} = -2.5 \log(F_{\nu}) - 48.59$, where F_{ν} is expressed in $\text{erg s}^{-1} \text{Hz}^{-1}$) for 3 different wavelengths: 1.2, 3.6 and $8 \mu\text{m}$. Figure 2 shows the colour-colour trajectory for PPGs with a Salpeter IMF with a low mass cutoff of $0.1 M_{\odot}$ (thin solid line), and $5 M_{\odot}$ (thick solid line), metallicity $Z = 0.01Z_{\odot}$, and an age of 10 million years. The dashed line is the evolution of the nearby starburst from Figure 1, and the dotted line the evolution of the idealized starburst model with no dust and $Z = 0.2Z_{\odot}$, also from Figure 1. All models have been simply K-corrected and the numbers that label the trajectories indicate the corresponding redshift. The figure shows that PPGs with redshift range $5 < z < 10$ have colors in the range of values $-3.0 \leq (1.2\mu\text{m}-8\mu\text{m})_{AB} \leq -2.0$ and $-0.9 \leq (3.6\mu\text{m}-8\mu\text{m})_{AB} \leq -1.5$, that are inside the dashed area. The idealized starburst model with no dust and sub-solar metallicity enters marginally the dashed area, but only for low redshifts ($z < 0.5$). This idealized model is unlikely to describe nearby galaxies, while it can be a rough description of the UV SED of quasars, in which case it could be concluded that PPGs should have very different colors than quasars at

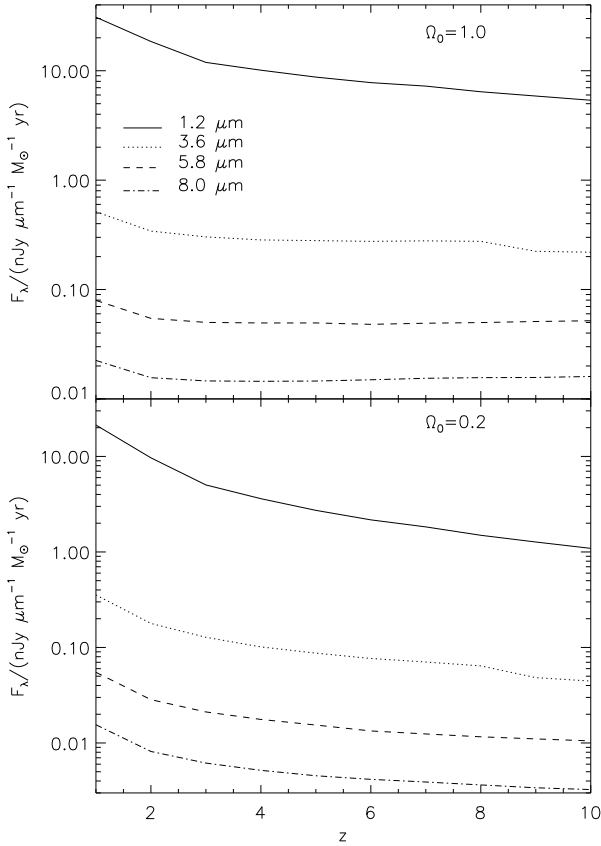


Figure 3. The expected IR flux density of PPGs, per unit of star formation rate, as a function of redshift, for four wavelengths and 2 cosmologies (in both cases $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Note that the cosmological dimming is very small since PPGs have $F_\nu \propto \nu^{1.5}$ (see Figure 1). The same model as in Figures 1 and 2 has been used, with a $5 M_\odot$ cutoff IMF. The flux density has been computed for an age of 0.01 Gyr, and increases rather slowly afterwards.

because only a finite fraction of the dark matter in stellar clusters or in the galactic halo and disk systems can be made of brown dwarfs (Gould, Bahcall & Flynn 1997; Reid & Gizis 1997; Kerins 1997; Gould, Flynn & Bahcall 1998; Reid et al. 1999). It is likely that while the local properties of the ISM do not interfere significantly with the self similar dynamics that originate the stellar IMF, they do play a role in setting the particular value of the mass scale where the self similarity is broken. According to this point of view, one expects the stellar IMF to have always more or less the same power law shape, down to a cutoff mass whose value depends on local properties of the ISM, and up to the largest stellar mass, whose value is limited either by the total mass of the star formation site, or by some physical process that prevents the formation of super-massive stars.

The lower mass cutoff of the stellar IMF has been predicted in models of i) opacity limited gravitational fragmentation (Silk 1977a; Silk 1977b; Silk 1977c; Yoshii & Saio 1985; Yoshii & Saio 1986); ii) protostellar winds that would stop the mass accretion onto the protostar (Adams & Fatuzzo 1996); iii) fractal mass distribution with fragmentation down to one Jeans' mass (Larson 1992). If gravitational sub-fragmentation during collapse is not very efficient (see Boss (1993)), the value of the Jeans' mass determines

the lower mass cutoff of the IMF. In Padoan, Nordlund & Jones (1997), numerical simulations of super-sonic and super-Alfvénic (Padoan & Nordlund 1999) magneto-hydrodynamic turbulence are used to compute the probability density function of the gas density, which is used to predict the distribution of the Jeans' mass in turbulent gas, under the reasonable assumption of uniform kinetic temperature. The Jeans' mass distribution computed in Padoan, Nordlund & Jones (1997) has an exponential cutoff below a certain mass value, that is found to be:

$$M_{\min} = 0.2 M_\odot \left(\frac{n}{10^3 \text{ cm}^{-3}} \right)^{-1/2} \left(\frac{T}{10 \text{ K}} \right)^2 \left(\frac{\sigma_v}{2.5 \text{ km/s}} \right)^{-1} \quad (1)$$

where T is the gas temperature, n the gas density, and σ_v the gas velocity dispersion. Using the ISM scaling laws, according to which $n^{1/2} \sigma_v \approx \text{const}$, one obtains:

$$M_{\min} \approx 0.1 M_\odot \left(\frac{T}{10 \text{ K}} \right)^2 \quad (2)$$

that is a few times smaller than the average Jeans mass (the Jeans mass corresponding to the average gas density), and therefore an important correction to more simple models of gravitational fragmentation, that do not take into account the effect of super-sonic turbulence on the gas density distribution.

If the ISM has primordial chemical composition, and the main coolant is molecular hydrogen, a temperature below 100 K is hardly reached, and the stellar IMF might have a lower mass cutoff of about $10 M_\odot$. Similar lower mass cutoffs are obtained in the models by Silk (1977c) and Yoshii & Saio (1986), who estimated typical stellar masses, based on molecular hydrogen cooling, of approximately 20 and $10 M_\odot$ respectively. More recent numerical simulations of the collapse and cooling of cosmological density fluctuations of large amplitude (the first objects to collapse in the Universe), yield even larger values of the Jeans' mass, of the order of $100 M_\odot$ (Bromm, Coppi, & Larson 1999; Abel, Bryan, & Norman 1998).

The discovery of PPGs could shed new light on the problem of the primordial IMF. The redshift evolution of the two colors $(1.2\mu\text{m}-8\mu\text{m})_{AB}$ and $(3.6\mu\text{m}-8\mu\text{m})_{AB}$, computed with the PPG model discussed in this work, is plotted in Figure 4. The solid line is the case of a PPG with a Salpeter IMF with $5 M_\odot$ cutoff, and the dashed line the same PPG model, but with a $0.1 M_\odot$ cutoff. Once a PPG candidate is selected with the IR broad band photometry as a very blue object (colors inside the shaded area in Figure 2), and its redshift is estimated with a Lyman drop method, or with an $H\alpha$ search, the IR colours provide a tool to discriminate between a standard IMF, and an IMF deprived of low mass stars. The lower panel of Figure 4 shows that a PPG with a 'massive' IMF can be about 0.5 mag bluer in $(1.2\mu\text{m}-8\mu\text{m})_{AB}$ than a PPG with a standard IMF.

5 DETECTABILITY VIA BROAD-BAND INFRARED IMAGING VERSUS EMISSION-LINE SEARCHES

In this work we propose to select PPGs as the bluest objects in deep IR surveys, on the basis of the color-color plot shown in Figure 2. We now address the question of how a broad band photometric selection of PPGs performs, compared with searches of emission lines, such as Lyman- α and $H\alpha$. The rest frame equivalent widths of Lyman- α and $H\alpha$ can be very roughly estimated by assuming that each photon below 1251 and 1025 Å will originate a

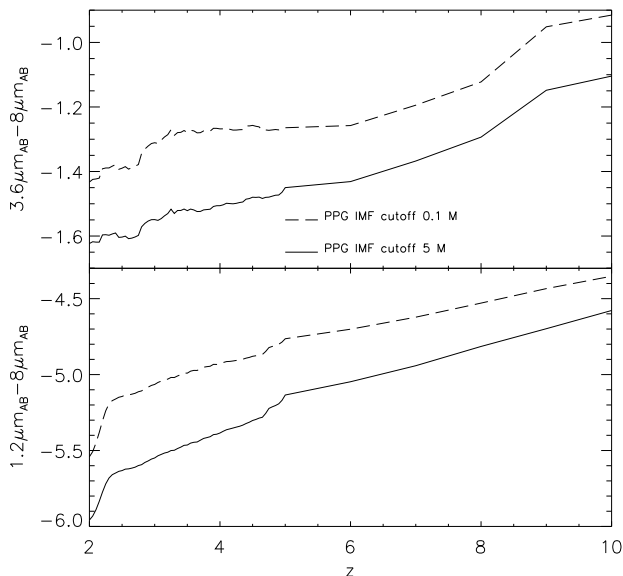


Figure 4. Colour evolution (AB system) with redshift for PPGs with a Salpeter IMF with $0.1 M_{\odot}$ cutoff (dashed line), and $5 M_{\odot}$ cutoff (solid line). As expected from Figure 1, the biggest difference occurs for colours that sample both the near-IR (rest-frame UV) and the far-IR. The difference between the Salpeter and the ‘massive’ IMF is about 0.5 mag in $(1.2\mu\text{m}-8\mu\text{m})_{AB}$. Once PPGs have been found at high z using the broad band color-color selection from Figure 2, and their redshift has been determined with narrow band photometry, the $(1.2\mu\text{m}-8\mu\text{m})_{AB}$ color can be used to discriminate among objects with a standard Salpeter IMF or a $5 M_{\odot}$ cutoff IMF.

Lyman- α and H- α photon respectively. The equivalent widths estimated in this way are of course upper limit to the true equivalent widths. We find that the equivalent width of Lyman- α is 380 \AA while the equivalent width of H- α is 4400 \AA –the latter is so high due to the fact that the continuum at 6563 \AA is rather faint in PPGs (see Fig. 1). Assuming that the lines have intrinsic widths at rest-frame typical of the virial velocity of a galaxy (for example a line width of 300 km/s corresponds to 2 and 13 \AA respectively), one finds that they will only be about 30 times brighter than the continuum at $z \sim 10$. Since one would need to shift the narrow filter for about 500 steps, or more, to search for all possible emitters in the redshift range $5 \leq z \leq 10$, the advantage of the lines being brighter than the continuum is offset by the number of steps needed to find all PPGs between $z = 5$ and 10 . It seems therefore that IR broad band photometry is an easier way to both detect and select PPG candidates than the emission line technique, because only one deep exposure is needed to find *all* PPGs in the redshift range $5 \leq z \leq 10$. Note that the equivalent width of Lyman- α and H- α has been over-estimated here. Moreover, the advantage of deep broad band photometry is that, together with detecting and selecting PPGs, it provides at the same time important information about their stellar populations. However, it is important that the emission line technique (or a Lyman break technique) is available aboard the NGST, since photometric redshifts measured with narrow filters will probably be the best (or the only) way to further constrain the redshift of PPG broad band photometric candidates, which is necessary to extract information about their stellar population from the broad band colors (Figure 4).

6 DISCUSSION AND CONCLUSIONS

We have studied the photometric properties of very young proto-galaxies with primordial or very low ($Z = 0.01Z_{\odot}$) metallicity and no significant effect of dust in their SED. We have named these galaxies ‘primordial protogalaxies’, or PPGs. Using the methods of synthetic stellar populations, we have shown that PPGs are the bluest stellar systems in the Universe. They can therefore be selected in color-color diagram obtained with deep broad band IR surveys, and can be detected with the NGST, if they have a SFR of at least $100 M_{\odot}/\text{yr}$, over a few million years. We have discussed the possibility of using the IR colours of PPGs to constrain their stellar IMF, and investigate the possibility that the stellar IMF arising from gas of primordial chemical composition is more ‘massive’ than the standard Salpeter IMF. Finally we have argued that broad band photometry can be more convenient than emission line searches, to detect and select PPGs.

It is possible that PPGs are rare because the chemical self-enrichment of a proto-galaxy could be very fast and efficient (Padoan, Jimenez & Jones 1997), or that they are difficult to detect, because population III stars could be formed at very large redshift ($z > 10$), in object of very low mass (e.g. Haiman, Thoul & Loeb (1996)). In order to enrich gas of primordial composition to a metallicity $Z = 0.01Z_{\odot}$, with a standard Salpeter IMF, it is necessary to convert into stars about 0.2% of the gas mass. A star formation rate of $100 M_{\odot}/\text{yr}$ over a few million years is necessary for detecting a PPG with the NGST. With such SFR, after 10^7 years $10^9 M_{\odot}$ of gas is turned into stars. In order to still have a metallicity of $Z \leq 0.01Z_{\odot}$, these stars must be formed in a system with baryonic mass of at least $1 \times 10^{11} M_{\odot}$, that is a very large galaxy, or a small group of galaxies. Such massive systems are inside large dark matter halos that are not collapsing yet at redshift $5 \leq z \leq 10$. It is possible that PPGs that can be detected with the NGST are the progenitors of very large galaxies, in a phase when their dark matter halo has not turned around yet. If PPGs are discovered, their spectro-photometric properties could give very important clues for the problem of star formation in galaxies (such as the origin of the stellar IMF) and their luminosity, abundance, and redshift distribution would trace the complete history of the very first star formation sites in the Universe.

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